Chapter Twenty-Seven

THE COSTS OF CLIMATE CHANGE TO THE UNITED STATES

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INTRODUCTION

Given the consequences that the other chapters of this book expect to result from global warming, it is hard to imagine that we would deliberately alter our planet in such a fashion. Yet preliminary analyses on the subject generally conclude that the value to society of avoiding these consequences is not as great as the cost of decreasing emissions, especially when one "discounts" future benefits to present values (e.g. Nordhaus 1990). This paper, however, makes two departures from previous studies, and thereby reaches a much higher estimate of the cost of heating our planet.

First, we focus on the range of uncertainty, rather than merely the central estimate, of a given impact. Focusing only on central estimates understates the value of an environmental risk because (a) our uncertainty tends to be skewed; (b) the damage function is often nonlinear; and (c) people are risk-averse. Suppose, for example, that our uncertainty regarding the impact of climate change on a farm is lognormal with the most likely impact a loss of 9 acre feet with nine-fold uncertainty; that the cost to the farmer is equal to number of acre feet lost, raised to the 1.5 power; and that people will pay 25 cents to avoid a risk that has a standard deviation of $1. Elementary probability theory shows that the expected decline in water would be 16.5 acre-feet; the expected cost would be $105, with a standard deviation of $395; hence, people would be willing to pay about $200 to avoid such a risk. By contrast, using only the best estimates and ignoring risk aversion would lead one to expect a loss of 9 acre-feet and a cost of only $27.

Second, we include environmental and other nonmarket impacts.[1] Because estimates of these assets range from poor to nonexistent, *we assume that society will undertake the necessary costs to offset environmental effects of global warming*.

The following sections (1) develop equations that summarize the nationwide impact of effects that have already been quantified; (2) develop state-by-state equations for four areas that have not been previously estimated in detail; (3) project the costs of climate change for two alternate emissions scenarios; and (4) calculate the benefits of reducing emissions. We assume that the U.S. economy will grow 1.2 to 2.1 percent per year. For the most part, our estimates are based on the GISS (Goddard Institute for Space Studies) and GFDL (Princeton Geophysical Fluid Dynamics Laboratory) models whose implications are discussed in detail by Smith and Tirpak (1989). Our calculations suggest that a CO_2 doubling would cost the United States $37-351 billion per year, with $92-130 billion most likely. At a 3% discount rate, the CO_2 from burning one gallon of gasoline will cause damages of 16-36 cents.

NATIONWIDE CALCULATIONS BASED ON SMITH AND TIRPAK (1989)

A previous EPA Report to Congress (Smith and Tirpak 1989) quantified costs for agriculture, energy consumption, and sea level rise. For those studies, our task is solely to interpret the results in a common framework that enables us to estimate the costs for different years and amounts of climate change. The EPA study also provided estimates of increased mortality, which can be readily monetized using existing estimates of the regulatory cost of saving lives.

Titus, J.G. 1992. *The Costs of Climate Change to the United States.* Originally published in: Majumdar, S.K., L.S. Kalkstein, B. Yarnal, E.W. Miller, and L.M. Rosenfeld (eds). *Global Climate Change: Implications, Challenges, and Mitigation Measures*. Pennsylvania Academy of Sciences. The format of this document has been modified for electronic distribution.

Agriculture

Crop modelers have already examined many of the ways by which global warming could affect agriculture, including longer growing seasons in colder areas, heat stress in the south, increased evaporation, changes in precipitation, the CO_2 fertilization effect, and changes in pests. Based on available studies, Adams et al. (1989) estimated the impact for the year 2060, assuming that CO_2 doubles and that the climate reaches the equilibria implied by the general circulation models. They reported that the GISS and GFDL models imply annual losses of 7.45 and 42.4 billion ($1984), ignoring CO_2 fertilization; and -$13.4 (net benefit) and $12.25 billion including CO_2 fertilization.[2]

Given these estimates, we need equations that can generalize the results for different climate scenarios and different years. (We use the term "generalize" to refer to both interpolation of smaller changes and extrapolation to larger changes). Our calculations employ separate equations for the GISS and GFDL models; we discuss only the former. Our low and high equations are as follows:

$\text{Cost}_{median} = 5.853\ T/T_{eq2} - 16.4\ CO_2^*$

$\text{Cost}_{low} = \text{Cost}_{median} - 3.7\ T/T_{eq2} - 6.129\ T/T_{eq2} - 4.1\ CO_2^*$

$\text{Cost}_{high} = \text{Cost}_{median} + 1\ T/T_{eq2} + 6.3\ T/T_{eq2} + 5.0\ CO_2^*$

where $CO_2^* = (CO_2-330)/330$ for $CO_2<660$ ppm

$= \ln (CO_2/330)/\ln(2)$ for $CO_2>660$ ppm

T = transient global temperature increase;

T_{eq2} = The model's estimated equilibrium warming for 2x CO2 and : We multiply these results by 1.005**(year-1985) to account for population growth and 1.263 to convert to $1990.

The median equation assumes that the climate impact is directly proportional to the change in global temperatures. Up to a doubling, we assume that the beneficial impacts of CO_2 are also linear. However, because crop modelers have noted that the beneficial impact of CO_2 eventually reaches a point of diminishing returns, we assume that the impact is only logarithmic past the doubling point (i.e. a CO_2 quadrupling has twice the beneficial impact of a CO_2 doubling). The low and high equations include Adams' yield uncertainties for climate and CO_2 fertilization.

Energy Consumption

Global warming would decrease energy consumption for space heating while increasing requirements for cooling. However, the cost of cooling a house one degree is greater than the cost of heating it one degree because (1) air conditioners require a more expensive form of energy (electricity) than home heating (mostly oil and natural gas); and (2) air conditioning takes place during peak hours while heating is mostly required at night.

Linder and Inglis (1989) developed a national model of how electricity consumption responds to temperature changes based on daily demand and weather data for five utility regions. They estimate that the increased consumption of electricity in the year 2060 implied by the GISS transient model would increase costs $37 billion with low economic growth and 53-81 billion ($1986) with high economic growth. Our generalizing equations are as follows:

$\text{Baseline} = P*\text{growth}*79.6$

$\text{electric}_{median} = (1.016^T-1)*\text{Baseline}$

$\text{electric}_{high} = \text{electric}_{median}*\sigma$

$\text{electric}_{low} = \text{electric}_{median}/\sigma$

where

T is transient global temperature increase;

P accounts for increasing price, assuming that (real) electricity prices grow 1.37% through 2060 and are stable thereafter; growth accounts for growth in electricity consumption, assuming that in the absence of climate change, consumption grows at 90 percent of the rate of general economic growth; and

σ represents a fourfold uncertainty for a given rate of growth.

These estimates fail to account for impacts of changing precipitation (e.g. pumping for irrigation) and adaptation (e.g. more insulation). They ignore the impact of global warming on the cost of meeting the increased demand, by assuming that it could be met by coal-fired utilities. If non-greenhouse gas sources are required, the unit generating costs may be greater; reduced availability for cooling water may also increase the costs of new capacity. We have not adjusted these calculations downward to account for reductions in space heating.[3]

Sea Level Rise

Global warming could raise sea level by (1) expanding seawater, (2) melting mountain glaciers, causing the ice sheets in (3) Greenland and (4) Antarctica to melt or discharge ice into the oceans, and by (5) depleting groundwater tables. Our calculations consider only the first three categories.

We used the same equations as IPCC for mountain glaciers and Greenland[4] for thermal expansion, we used the model developed by Hoffert *et al*. (1980) to specify these equations, with B=0 for the low scenario and B=1 for the high estimate (B is the ratio of temperature increase at the surface to temperature increase at the bottom of the ocean). In both cases, we ran the model for 500 years for an assumed warming of 2^{o}C. In the low case, the rise was 18, 24, and 30 cm after 100, 200 and 500 years, respectively. For the high case, the rise was 21, 33, and 59 cm.

We then estimated the following regression equations.

$$\begin{aligned}\mathrm{Expand}_{\mathrm{low}}(t) = {} & 1.26T(t-1) - 1.24T(t-2) + 0.104T(t-3) + 0.0141T(t-4) \\ & + 0.003393T(t-5) + 1.712\ \mathrm{Expand}_{\mathrm{low}}(t-1) - 0.721\ \mathrm{Expand}_{\mathrm{low}}(t-2)\end{aligned}$$

$$\begin{aligned}\mathrm{Expand}_{\mathrm{high}}(t) = {} & 1.24T(t-1) - 1.3383T(t-2) + 0.1374T(t-3) + 0.023386T(t-4) + 0.009048T(t-5) + \\ & 0.003804T(t-6) + 1.796957\ \mathrm{Expand}_{\mathrm{low}}(t-1) - 0.79832\ \mathrm{Expand}_{\mathrm{low}}(t-2)\end{aligned}$$

where T represents transient global temperature and both equations use time steps of 5 years. In each case the R-squared was greater than 0.9999.

Note that these equations use first and second order lagged dependant variables. The effect of doing so is to impose the assumption that after the first 5 or 6 time periods, the effect of a temperature increase diminishes as the sum of two declining exponentials. The adjustment times for the low and high equations are 100 and 600 years. Figure 1 shows the resulting sea level rise projections.

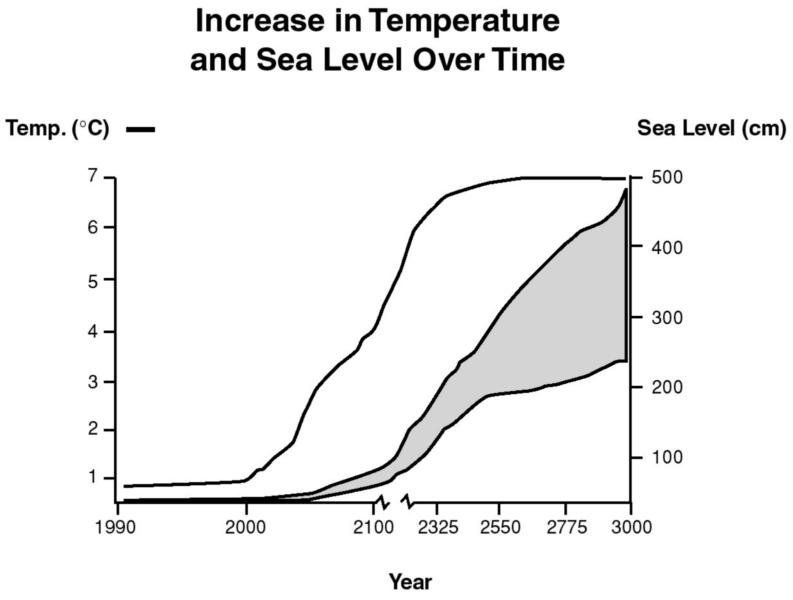

FIGURE 1. Sea level curves show the range of uncertainty given the trend for temperatures. The temperature curve starts at 0.5°C to account for past warming due to greenhouse gases.

Using those projections, we estimated the costs of sea level rise for wetland loss, dike construction, land for dikes, loss of dry land, beach nourishment, and the cost of elevating infrastructure in low areas, based on Titus *et al*. (1991). For each of the cost categories, that study had reported low and high estimates for the 12 (baseline), 50, 100, and

200 centimeter scenarios. For sea level rise less than 200 cm, this analysis interpolates those estimates to calculate the total cost of sea level rise by a given year. For dry-land loss and dike costs, we assume that development in coastal areas will grow at the same rate as the general economy; but we assume that does not increase wetland loss or the cost of protecting barrier islands.

The slope of coastal lands is generally much steeper above the one-meter contour than below. Thus, for sea level rise greater than 200 cm, our calculations for elevating structures and loss of dry land assume costs rise at the same rate as for a rise of 100 to 200 cm. We assume that a 3.3 meter rise would inundate the remaining coastal wetlands, and interpolate linearly. For sand, we assume that the incremental costs stay the same. For dikes, we assume that costs rise with the 1.5 power of sea level rise.

Health

Heat- and cold-related mortality are the only health impacts of global warming that have been quantified. Kalkstein (1989) estimates that given today's population in the 15 largest cities, a CO_2 doubling would increase heat-related deaths 529-3878 among the elderly and 513-2368 among other age groups, while reducing cold-related deaths by 59-123 and 25-68 among the two groups. Fisher et al. (1989) estimate that the value of reducing the risk of a statistical death is between $1.6 and 8.5 million; this estimate does not say how much a human life is worth, but rather the extent to which society currently invests resources to avoid deaths from pollution and accidents.

We generalize the relationships as follows:

$\text{Deaths}_{\text{high}} = 6110\ T$

$\text{Deaths}_{\text{low}} = 1646\ T$

$\text{Costh}_{\text{high}} = 8{,}500{,}000\ \text{Deaths X growth}$

$\text{Cost}_{\text{low}} = 8{,}500{,}000\ \text{Deaths X growth}$

where growth represents economic growth as described above.

STATE BY STATE CALCULATIONS OF EFFECTS NOT PREVIOUSLY QUANTIFIED

For the impacts not previously quantified, calculating impacts on a state-by-state basis seemed to be an appropriate level of aggregation. The national level is too broad because it can not capture all the ambiguities, such as (1) some areas becoming wetter while others become colder; and (2) a warmer or dryer climate helping a cold area suffering from too much rainfall, while harming a warm area where water supplies are only barely adequate. By contrast, state-level analyses can capture these regional differences.

We generated our scenarios for annual and summer changes in climate by assuming that (1) the climate of a state is characterized by the climate of its capital; (2) the change in temperature for a CO_2 doubling is characterized by the difference between temperatures projected by the doubled CO_2 and control runs of the GISS and GFDL models; (3) the change in rainfall for a CO_2 doubling is characterized by the ratio of changes implied by the doubled CO_2 and control runs; and (4) the change in rainfall or temperature by a particular year is proportional to the change in global temperatures.

Automobile Air Conditioners

Warmer temperatures will lead motorists to run their air conditioners a greater percentage of the time. General Motors estimates that the average automobile in the United States uses 20 gallons of gasoline to run its air conditioner for every 10,000 miles driven. It also estimates that on days with a daily average temperature of 50, 60, and 90 degrees (F), that 0, 30, and 90 percent of all miles driven by automobiles with air conditioners are driven with the air conditioners on.[5] These assumptions imply that the U.S. currently consumes 3.84 billion gallons per year on automobile air conditioning.

Our calculations use those results along with the assumption that fuel consumption is proportional to the difference between the daily average temperature and 50^{o} F.

Air Pollution: Ozone

Climate plays an important role in determining whether air pollutants are transported out of harms way or linger enough to threaten people's health. Of the many ways by which global warming could change air quality, the only quantified so far is the impact of warmer temperatures on the formation of tropospheric ozone.

Gerry (1987) estimated the possible impacts of 2^0 and 5^0 C warmings on ozone concentrations in Los Angeles, New York, Philadelphia, and Washington,[6] with ozone concentrations increasing 1.6875 $\underline{+}$ .3684 percent per degree warming. Morris *et al*. (1988) applied a regional transport model to central California and the part of the United States (approximately) between 78^o and 98^oN longitude (that is, west of central Maryland and east of San Antonio Texas.) They found that maximum ozone concentrations would increase 1.4525 $\underline{+}$ .497 percent per degree warming.[7] Because Gerry and Morris *et al*. reach similar results, we assume that ozone concentrations increase 1.5+0.5 percent per degree warming.

Estimating the cost of preventing such an increase requires us to consider (a) the percentage reduction in emissions, (b) the absolute level of emissions that would otherwise occur, and (c) the cost of reducing emissions by one ton. Smith and Tirpak (1988) estimate that the 6% increase on ozone concentrations implied by Morris *et al*. would require emissions of volatile organic compounds (VOC) to be reduced 11.7%; hence we assume that the reduction in VOC would be 1 to 2% for every 1% increase in ozone concentrations.

Pechan Associates (1990) estimate that the baseline emissions for 2005 would be approximately 14 million tons, and that emissions are increasing by about 3% per year. They also estimate that the incremental cost of reducing emissions currently ranges from \$1700 to \$5000. Smith and Tirpak state that the cost is \$5000. EPA's Office of Air Quality Planning and Standards told us that even at the \$5000/ton cost, the available emission reductions are not unlimited. Nevertheless, we assume that emissions can be controlled for \$1700-5000 per ton.

WATER RESOURCES

Rising temperatures and reduced rainfall could increase the demand for irrigation water and diminish the supply of water for all uses. The resulting reductions in river flows would reduce hydropower production and worsen water quality (unless the discharge of pollutants was also reduced).[8]

Baseline Conditions

Our starting points are USGS data on withdrawals of ground and surface water by the agriculture, residential, and industrial sectors of each state. Based on Gibbons (1988), we assume that the price of surface water is currently \$35-85 per acre foot, and that the elasticity of demand for water is between 0.5 and 1.0.[9] We assume the same range for elasticity of supply, which is probably optimistic because (a) in the west current supplies are already oversubscribed, and (b) in the east, water experts generally doubt that any more major dams will be built due to the adverse environmental effects. We assume that residential and industrial demand increase by the same rate as economic growth, but that irrigation demand does not increase. As Table 1 shows, our baseline water prices range from \$60 to \$250 per acre-foot by 2060.

Our approach is similar for groundwater. However, in those regions where the ratio of groundwater overdraft to recharge was greater than 0.2, we assume that the current price of water is the same as the surface price, and that there is a near-fixed supply elasticity of 0.1. Where there is no overdraft, we assume that unlimited water can be pumped for \$10 per acre-foot. For intermediate cases, we interpolate between these two assumptions.

TABLE 1
Regression Equations Predicting Irrigation Per Acre As A Function of Climate Change

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SOUTHEAST (Results Assume 600 ppm CO_2 fertiliztion)

$$\Delta\ln(\text{Soy Irrigation}) = \underset{(0.365)}{0.05\Delta T,ja} - \underset{(0.0891)}{0.619\Delta\ln(Pjja)}$$

$R^2 = 0.745$ S.E. = 0.087

$$\Delta\ln(\text{Corn Irrigation}) = \underset{(0.372)}{0.0200\Delta Tjja} - \underset{(0.0808)}{0.592\Delta\ln(Pjja)}$$

$R^2 = 0.9400$ S.E. = 0.0372

GREAT PLAINS (Results Ignore CO_2 fertilization)

$$\Delta\ln(\text{Corn Irrigation}) = \underset{(0.373)}{0.0172\Delta Tjja} - \underset{(0.00252)}{0.45567\text{Î}\ln(Pjja)}$$

R2= 0.833 S.E. = .0387

$$\Delta\ln(\text{Wheat Irrigation}) = \underset{(0.116)}{0.1763\Delta T} \underset{(0.250)}{-1.25\Delta\ln(P)} + \underset{(0.001911)}{0.00918\Delta\ln(Yield)}$$

R2= 0.551 S.E. = 0.0348

GREAT LAKES

With 600 ppm CO_2 fertiliztion

$$\Delta\ \%\ \text{Soy Irrigation} = -0.684 + \underset{(0.0387)}{0.193\Delta Tjja} \underset{(0.467)}{-0.687\Delta\%Pjja} + \underset{(0.0432)}{0.165\Delta\%Yield}$$

R2= 0.849 S.E. = 0.226

$$\Delta\ \%\ \text{Corn Irrigation} = -1.05 + \underset{(1.23)}{0.0712\Delta Tjja} + \underset{(0.127)}{0.408\Delta\%Yield}$$

R2= 0.511 S.E. = 0.125

Without CO2 fertilization

$$\Delta\ \%\ \text{Soy Irrigation} = \underset{(0.0137)}{0.0855\Delta Tjja} \underset{(0.4113)}{-1.5523\Delta\%Pjja} + \underset{(0.1253)}{0.360\Delta\%Yield}$$

R2= 0.659 S.E.= 0.3186

$$\Delta\ \%\ \text{Corn Irrigation} = \underset{(0.017)}{0.0697\Delta Tjja} - \underset{(0.127)}{1.539\ \Delta\%Pjja} + \underset{(0.2445)}{1.0012\Delta\%Yield}$$

$R^2= 0.5353$ S.E.= 0.331

Combined

$$\Delta\ \%\ \text{Soy Ir} = \underset{(0.0111)}{0.0900\Delta Tjja} \underset{(0.2647)}{-1.5817\Delta\%Pjja} + \underset{(0.0484)}{0.202\Delta\%Yield} - \underset{(0.00022583)}{0.000763\Delta\ CO2}$$

R2= 0.736 S.E.= 0.2841

$$\Delta\ \%\ \text{Corn Ir} = \underset{(0.0126)}{0.0641\Delta Tjja} - \underset{(0.265)}{0.729\ \Delta\%Pjja} + \underset{(0.143)}{0.562\Delta\%Yield} \underset{(0.000201)}{-0.00322\Delta\ CO2}$$

R2= 0.8004 S.E.= 0.2848

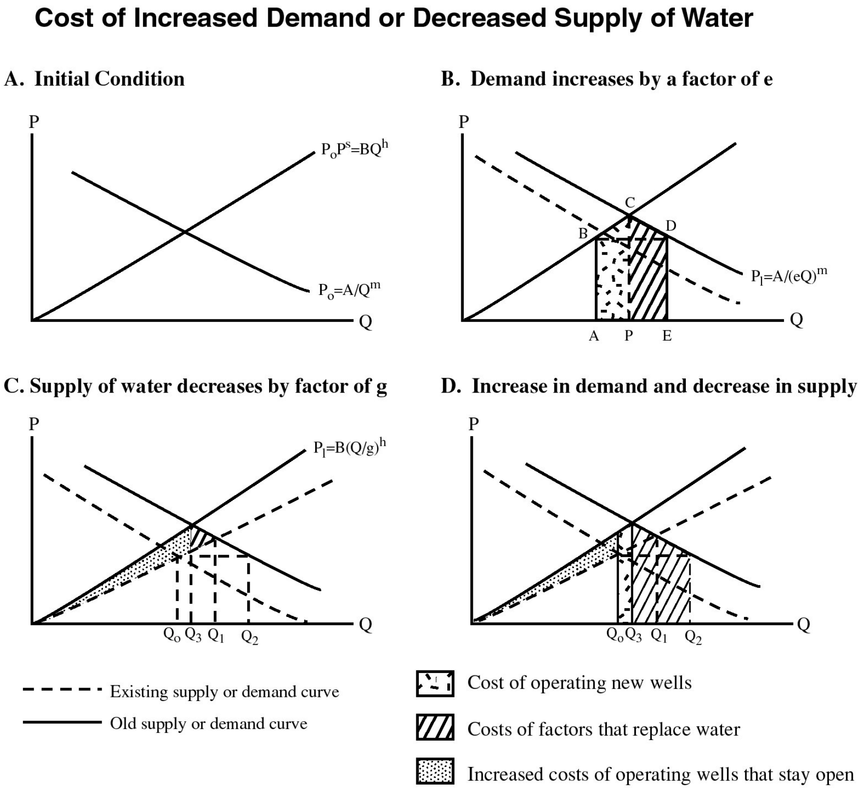
Changes in Supply and Demand

Previous studies have estimated changes in water requirements (per acre) for a dozen or so sites that are already irrigated in the Southeast (Peart et al. 1989), Great Plains (Rosensweig), and the Great Lakes Region (Ritchie).[10] We estimate summary regression equations, shown in Table 1.[11] We used the state-specific results of Peterson and Keller (1990) as low and high estimates of the elasticity of irrigated acreage with respect to temperature and precipitation.

Finally, residential lawn watering and other outdoor uses would also change. Because only 25% of residential use is consumptive, we assume that it would increase by 25% of the fraction by which irrigation per acre increases in a given state. We include this impact within irrigation demand. We calculate the increased cost of delivering more water to residential users, based on the current difference between residential and market prices.

The supply of water could change for two reasons: (1) more (or less) rainfall would increase (decrease) the amount of water flowing in rivers and recharging aquifers; and (2) higher temperatures increase evaporation and hence reduce the availability of water if nothing else changes. We use the simple model from Waggoner and Revelle (1990) which assumes that runoff decreases 2-4 percent if either (a) precipitation decreases 1 percent or (b) temperature increases 0.4^o. We assumed that in the west, river flow, groundwater, and surface supplies available for withdrawal decline by the same fraction as runoff. For the east, our assumptions are the same, except that because flows are very large relative to withdrawals, we assume that runoff changes have no impact on surface supplies.[12]

If the change in climate is small, the cost to society can be calculated simply as the price of water times the sum of the increase in demand plus the decrease in supply. But for large changes, this assumption understates the impact because as prices rise, each additional shift in supply or demand costs more than the previous shift. Figure 2 illustrates the general case. As demand increases, more water must be delivered; prices will rise, which will lead some current users to conserve water and spend more on labor, fertilizer, or some other factor of production to achieve a harvest of a given size.


Cost of Increased Demand or Decreased Supply of Water

A. Initial Condition

B. Demand increases by a factor of e

C. Supply of water decreases by factor of g

D. Increase in demand and decrease in supply

FIGURE 2.

The cost of a reduction in supply can also be divided into increased extraction cost and the cost of conserving water. In Figure 2c, the left triangle shows the increased cost of supplying water from the preexisting pumps that continue to operate. The right triangle illustrates the difference between the value of using water for users who choose to consume at a higher price and the previous cost of pumping from wells that are closed due to the increased cost.

We do not allow for water being transported between states; nor do we allow for consumers to switch between ground and surface water. To prevent anomalies, in which dramatic supply and demand crunches cause implausible price rises, we assume that a state can always build a project that provides all of the increased water requirements for $300 to 700 per acre foot.

Water Pollution and Hydropower

We assume that the discharge of pollutants would change by the same proportion as does river flow, to maintain current water quality. EPA's 1990 Report to Congress on the Cost of a Clean Environment reports that state and local water pollution costs for point sources (mostly sewage treatment plants) are growing at 3.6 percent per year and will be $18.8 billion by the year 2000. Other costs (mostly industrial) are growing at 4.5 percent per year and will reach $45.3 billion by the year 2000. We assume that in the baseline, these costs would only grow in step with the general economy after 2000.

According to EPA Region III, assuming that one has already achieved secondary (85%) control, the cost elasticity for further control is about -1.0. For the last several years, each industry-specific water-quality regulation issued by EPA has been accompanied by a Regulatory Impact Assessment, which must estimate the marginal cost of controlling pollutants under the regulation, as well as an estimate of the marginal cost of the next more stringent technology. Based on these analyses, we assume elasticities of 1.0 to 1.73.

We assume that hydropower production declines in proportion to the change in runoff, using data on current hydropower from Edison Electric Institute (1985). We assumed that there will be no increase in generating capacity.

Results

Tables 2 and 3 illustrate our intermediate calculations of surface water supply and demand, based on the GISS general circulation model. We display our results at the state level *only* to permit the reader to better understand the limitations of our calculations. Our nationwide results are presented both in (a) $1990 and (b) $1990 scaled downward to account for economic growth. Note that for surface water, the uncertainty surrounding our baseline assumptions is greater than the impact of climate change. Nevertheless, our equations imply that increased demand for irrigation water could raise the total demand for water by 10 percent for about 10 states. About three quarters of the states would experience declines in water supplies while the rest would have increased availability. The scaled cost of these changes would be $1-3 billion per year for the GISS scenario and $3-7 billion for GFDL.

Table 4 illustrates our groundwater calculations for both the low and high scenarios. Although the low-growth scenario implies that none of the states would be paying over $200/acre foot, the high-growth scenario has 24 states doing so, with 13 states paying over $500/acre-foot (at the margin). The scaled cost under the GISS scenario would be $1.1-4.6 billion per year for the GISS scenario and $1.5-6 billion for GFDL.

Finally, Table 5 illustrates our estimates for the other water resources and the total cost. The water *quality* problems of global warming would be more expensive than the water *quantity* problems. Under GISS, (scaled) pollution control costs would increase $15-52 billion (compared with a base of $64 billion), with the total water resource costs $21-60 billion. With GFDL, the costs is $31-87 billion, of which $21-67 billion is for pollution control. Nevertheless, some areas might have more favorable conditions. Under the GISS scenario, wetter conditions in the Pacific Northwest would increase hydropower production by 2-5 billion (unscaled) dollars, more than offsetting declines in California and Washington. However, the dry conditions of the GFDL scenario would lead hydropower production to decline in every state for a total loss of 4-13 billion (unscaled) dollars.

Table 2
Change in Surface Water Supply and Demand for GISS CO_2 Doubling Low Scenario

State	Consumption		Price					Cost	
	Base	Climate Change	PO	P1	% Change Irrigation	% Change Demand	% Change Supply	Demand	Supply
AL	17.52	15.63	85	96	215.33	0.24	-20.64	3.59	.00
AZ	3.60	3.34	58	63	1.22	.97	-14.70	2.05	48.15
AR	4.76	4.46	80	94	110.41	10.64	-20.64	41.67	136.01
CA	29.97	27.85	60	76	24.91	17.21	-26.35	327.07	891.27
CO	16.11	16.63	60	72	34.11	23.65	-13.82	243.12	256.04
CT	2.09	1.82	85	98	89.54	0.56	-24.70	1.00	.00
DE	.10	.10	84	81	46.21	-0.47	6.43	-0.04	.00
FL	5.54	4.86	75	92	37.86	7.91	-28.57	33.55	.00
GA	9.54	9.88	84	82	63.09	0.83	6.43	6.67	.00
ID	24.57	26.40	66	59	-9.84	-4.43	20.84	-71.67	.00
IL	28.05	26.46	85	90	78.59	-0.06	-11.00	-1.38	.00
IN	22.78	21.50	85	90	78.93	0.03	-11.00	.59	.00
IA	4.02	3.80	85	90	130.56	0.37	-11.00	1.28	58.05
KS	1.47	1.34	73	106	124.31	31.69	-37.18	36.68	85.92
KY	7.71	7.95	85	82	53.17	-0.25	6.43	-1.64	.00
LA	18.60	17.10	82	97	159.06	8.29	-21.92	129.80	.00
ME	1.35	1.18	85	98	378.67	1.20	-24.70	1.39	.00
MD	1.70	1.75	85	82	82.31	0.26	6.43	-0.37	.00
MA	3.67	3.19	85	98	91.92	0.22	-24.70	0.70	.00
MI	24.49	20.29	85	103	168.38	0.65	-31.81	13.64	.00
MN	4.20	3.97	85	90	175.69	0.48	-11.00	1.72	.00
MS	2.39	2.20	83	96	182.69	7.36	-20.64	14.86	.00
MO	11.21	10.00	85	96	138.39	0.27	-20.64	2.55	309.08
MT	13.12	14.76	58	55	8.86	7.08	18.27	54.94	-217.84
NE	7.65	7.69	71	83	59.01	17.13	-13.82	97.95	136.76
NV	3.49	3.09	58	70	8.67	6.98	-26.35	14.52	91.06
NH	.56	.49	85	98	378.67	0.96	-24.70	.46	.00
NJ	3.67	3.21	85	99	109.41	1.28	-24.70	4.03	.00
NM	2.43	2.43	56	66	18.88	16.83	-14.70	24.08	36.42
NY	12.61	11.02	85	99	431.80	1.47	-24.70	15.90	.00
NC	12.75	13.17	85	82	68.00	0.27	6.43	2.88	.00
ND	15.91	14.86	85	92	311.99	1.19	-13.82	16.14	291.91
OH	22.79	18.83	85	103	167.98	0.13	-31.81	2.57	.00
OK	1.26	1.04	80	106	102.45	9.64	-37.18	10.02	67.30
OR	6.93	7.64	59	54	.80	.44	20.84	1.80	-125.31
PA	26.23	21.86	85	104	422.65	1.83	-31.81	41.12	.00
RI	.24	.21	84	98	90.15	1.27	-24.70	.26	.00
SC	9.80	10.12	85	82	77.58	.16	6.43	1.35	.00
SD	.44	.65	59	102	214.37	153.78	-13.82	51.71	14.30
TN	16.83	15.00	85	96	230.71	.08	-20.64	1.13	.00
TX	9.18	8.31	71	96	70.14	22.61	-33.20	155.25	426.99
UT	4.34	4.62	62	56	-6.58	-4.21	18.27	-11.28	-69.09
VT	.53	.46	85	98	321.27	.43	-24.70	0.19	.00
VA	9.11	9.39	85	82	31.32	-.08	6.43	-0.61	.00
WA	9.47	10.68	61	54	-1.32	-1.13	28.45	-6.56	.00
WV	9.47	9.76	85	82	-2.57	-.09	6.43	-.73	.00
WI	89.12	8.60	85	90	284.09	.03	-11.00	.23	.00
WY	5.62	5.80	57	68	27.71	23.84	-13.82	80.74	84.45
US	(Scaled and including price uncertainty)							36.5	551.5

Note: PO and P1 = baseline and greenhouse-induced price of water ($/ac-ft)
Costs are in millions of dollars per year; quantities are in millions of acre-feet per year.

Table 3
Change in Surface Water Supply and Demand for GISS CO_2 High Scenario

	Consumption		Price					Cost	
State	Base	Climate Change	PO	P1	% Change Irrigation	% Change Demand	% Change Supply	Supply	Supply
AL	24.42	19.95	259	389	232.94	.15	-33.35	9.82	.00
AZ	3.94	3.44	75	100	1.27	.85	-24.43	2.52	60.24
AR	6.48	5.49	217	351	148.08	7.71	-33.35	110.68	472.60
CA	34.30	28.12	88	174	27.00	14.71	-41.41	464.25	1530.54
CO	18.30	17.55	86	133	36.20	19.49	-23.06	321.94	385.16
CT	2.91	2.30	256	432	156.21	2.52	-39.13	18.96	.00
DE	.14	.14	252	223	50.53	-1.14	11.77	-0.39	.00
FL	5.54	4.86	75	92	37.86	7.91	-28.57	33.55	.00
GA	9.54	9.88	84	82	63.09	0.83	6.43	6.67	.00
ID	24.57	26.40	66	59	-9.84	-4.43	20.84	-71.67	.00
IL	28.05	26.46	85	90	78.59	-0.06	-11.00	-1.38	.00
IN	22.78	21.50	85	90	78.93	0.03	-11.00	.59	.00
IA	4.02	3.80	85	90	130.56	0.37	-11.00	1.28	58.05
KS	1.47	1.34	73	106	124.31	31.69	-37.18	36.68	85.92
KY	7.71	7.95	85	82	53.17	-0.25	6.43	-1.64	.00
LA	18.60	17.10	82	97	159.06	8.29	-21.92	129.80	.00
ME	1.35	1.18	85	98	378.67	1.20	-24.70	1.39	.00
MD	1.70	1.75	85	82	82.31	0.26	6.43	-0.37	.00
MA	3.67	3.19	85	98	91.92	0.22	-24.70	0.70	.00
MI	24.49	20.29	85	103	168.38	0.65	-31.81	13.64	.00
MN	4.20	3.97	85	90	175.69	0.48	-11.00	1.72	.00
MS	2.39	2.20	83	96	182.69	7.36	-20.64	14.86	.00
MO	11.21	10.00	85	96	138.39	0.27	-20.64	2.55	309.08
MT	13.12	14.76	58	55	8.86	7.08	18.27	54.94	-217.84
NE	7.65	7.69	71	83	59.01	17.13	-13.82	97.95	136.76
NV	3.49	3.09	58	70	8.67	6.98	-26.35	14.52	91.06
NH	.56	.49	85	98	378.67	0.96	-24.70	.46	.00
NJ	3.67	3.21	85	99	109.41	1.28	-24.70	4.03	.00
NM	2.43	2.43	56	66	18.88	16.83	-14.70	24.03	36.42
NY	12.61	11.02	85	99	431.80	1.47	-24.70	15.90	.00
NC	12.75	13.17	85	82	68.00	0.27	6.43	2.88	.00
ND	15.91	14.86	85	92	311.99	1.19	-13.82	16.14	291.91
OH	22.79	18.83	85	103	167.98	0.13	-31.81	2.57	.00
OK	1.26	1.04	80	106	102.45	9.64	-37.18	10.02	67.30
OR	6.93	7.64	59	54	.80	.44	20.84	1.80	-125.31
PA	26.23	21.86	85	104	422.65	1.83	-31.81	41.12	.00
RI	.24	.21	84	98	90.15	1.27	-24.70	.26	.00
SC	9.80	10.12	85	82	77.58	.16	6.43	1.35	.00
SD	.44	.65	59	102	214.37	153.78	-13.82	51.71	14.30
TN	16.83	15.00	85	96	230.71	.08	-20.64	1.13	.00
TX	9.18	8.31	71	96	70.14	22.61	-33.20	155.25	426.99
UT	4.34	4.62	62	56	-6.58	-4.21	18.27	-11.28	-69.09
VT	.53	.46	85	98	321.27	.43	-24.70	0.19	.00
VA	9.11	9.39	85	82	31.32	-.08	6.43	-0.61	.00
WA	9.47	10.68	61	54	-1.32	-1.13	28.45	-6.56	.00
WV	9.47	9.76	85	82	-2.57	-.09	6.43	-.73	.00
WI	89.12	8.60	85	90	284.09	.03	-11.00	.23	.00
WY	5.62	5.80	57	68	27.71	23.84	-13.82	80.74	84.45
US	Adding in the price uncertainty							1763.7	2715.6

Note: P0 and P1 = baseline and greenhouse-induced price of water ($/ac-ft)\
Costs are in millions of dollars per year; quantities are in millions of acre-feet per year.

Table 4
Change in Groundwater Supply and Demand for GISS CO_2 Doubling

State	Overdraft		Elasticity		PO		P1		Demand Cost		Supply Cost	
	L	H	L	H	L	H	L	H	Low	High	Low	High
AL	0.18	0.42	∞	0.1	50	50	500	1077	0.8	3.2	0	100.9
AZ	0.65	0.88	0.1	0.1	61	72	93	150	1.6	3.7	84.9	132.6
AR	1.68	2.6	0.1	0.1	67	135	131	598	165.4	472.6	205.6	741.7
CA	0.25	0.43	0.1	0.1	71	106	156	450	117.4	333.7	677.2	2291.8
CO	0	0	∞	∞	10	10	10	10	16.5	10.3	0	0
CT	0	0	∞	∞	10	10	10	10	0	0.1	0	0
DE	0.02	0.04	∞	∞	12	12	16	16	0	0	0	0
FL	0.16	0.36	∞	0.1	45	45	374	1097	27.2	115.2	0	1460.4
GA	0.12	0.2	∞	0.1	35	35	440	394	7.2	34.1	0	-77.5
ID	0.11	0.17	∞	0.3	34	34	187	121	-14	-6.7	0	-657.8
IL	0	0	∞	∞	10	10	10	10	-0.1	0.2	0	0
IN	0	0	∞	∞	10	10	10	10	1.3	0.9	0	0
IA	0.68	1.4	0.1	0.1	117	136	500	741	3.5	20.2	30.7	138.8
KS	0.9	1.47	0.1	0.1	61	174	88	1045	299.3	618.7	461.9	2084.1
KY	0	0	∞	∞	10	9	10	10	0	0	0	0
LA	0.29	0.51	0.1	0.1	89	156	315	969	58	211.8	106.8	556.5
ME	0	0	∞	∞	10	10	10	10	0	0	0	0
MD	0.02	0.04	∞	∞	12	12	17	17	0.1	0	0	0
MA	0	0	∞	∞	10	10	10	10	0	0.2	0	0
MI	0.07	0.17	∞	0.3	23	23	304	803	3.3	26.4	0	243.2
MN	0	0	∞	∞	10	10	10	10	2	1.9	0	0
MS	0.3	0.5	0.1	0.1	84	162	268	964	67.5	245.5	912.2	456
MO	0.76	1.69	0.1	0.1	109	150	500	#	4.9	47.2	26.7	158.6
MT	0.38	0.58	0.1	0.1	93	80	353	220	0.2	1.9	-23.6	-26.8
NE	0.64	1.27	0.1	0.1	105	128	499	824	38.9	200.4	268.7	1434.2
NV	0.83	1.51	0.1	0.1	73	101	176	460	1.7	6.2	27.5	99.8
NH	0	0	∞	∞	10	10	10	10	0	0	0	0
NJ	0.03	0.08	∞	0.8	15	15	79	116	0.9	3	0	56.9
NM	0.45	0.68	0.1	0.1	65	84	117	238	11.1	41.1	45.7	98.8
NY	0.03	0.08	∞	0.8	15	15	82	121	1.3	3.8	0	59.1
NC	0.13	0.25	∞	0.1	39	39	500	419	0.7	3.3	0	-57.2
ND	0.73	1.53	0.1	0.1	119	145	500	818	5.3	22.1	38.5	183.8
OH	0	0	∞	∞	10	10	10	9	0.1	0.3	0	0
OK	2.12	4.35	0.1	0.1	78	167	215	#	26.8	105.6	76.9	481.7
OR	0.1	0.14	∞	0.5	31	31	97	69	0	1	0	-38.8
PA	0.04	0.09	∞	0.7	16	16	100	173	1	2.9	0	121.1
RI	0	0	∞	∞	10	9	10	9	0	0	0	0
SC	0.13	0.24	∞	0.1	39	39	500	417	0.2	0.6	0	-16.3
SD	0.79	1.31	0.1	0.1	92	155	346	867	13.4	54.1	15.3	70.2
TN	0	0	∞	∞	10	10	10	10	1.1	1	0	0
TX	2.14	3.71	0.1	0.1	70	138	148	751	222.6	588	611.8	2584.1
UT	0.44	0.53	0.1	0.1	69	56	142	80	-2	-5.7	-56.7	-31.3
VT	0	0	∞	∞	10	10	10	10	0	0	0	0
VA	0.02	0.04	∞	∞	12	12	17	17	0	0	0	0
WA	0.12	0.2	∞	0.1	36	36	434	260	-0.6	71.1	0	-198.5
WV	0	0	∞	∞	10	10	10	9	0	0	0	0
WI	0	0	∞	∞	10	10	10	10	1.5	0.9	0	0
WY	0.43	0.64	0.1	0.1	67	89	127	260	4.1	13.9	11.9	26.7
US	(Scaled, including price uncertainty)								223	1263	639	4479

Note: # Supply curve shift is unrealistically costly; hence we assume that project is built that delivers water for $800/acre-foot.
See Table 2 for explanation of other units.

Table 5
Other Water Related Costs for GISS CO_2 Doubling
($ millions, scaled for economic growth)

State	Residential		Pollution		Hydropower		Total Water Costs ($Billions)			
	Low	High	Low	High	Low	High	Low	Medium	High	Mean
AL	13.5	33.8	277.2	858.9	39.2	114.1	.4	.6	1.0	.7
AZ	.1	.4	152.1	478.1	40.9	120.6	.2	.4	.7	.5
AR	3.2	16.0	162.3	502.8	9.9	28.8	.3	.6	1.2	.8
CA	15.6	77.5	2708.7	8275.9	198.7	571.8	3.8	6.3	10.5	7.2
CO	4.1	20.3	133.2	419.8	61.9	183.0	.4	.6	.9	.6
CT	-9.7	28.0	281.0	862.1	1.6	4.6	.3	.5	.9	.6
DE	.4	1.1	-30.6	-23.2	0.0	0.0	.0	.0	.0	.0
FL	1.5	3.8	1335.5	4058.5	1.1	3.0	1.6	2.6	4.3	3.0
GA	6.5	16.3	-294.3	-222.6	-4.8	-14.8	-.1	-.2	-.3	-.2
ID	.0	-.1	-130.4	-98.0	-50.7	-162.3	-.2	-.3	-.4	-.3
IL	-39.2	111.5	357.1	1132.8	0.2	0.7	.4	.7	1.2	.8
IN	-10.5	31.7	171.0	542.5	0.9	2.5	.2	.3	.6	.4
IA	1.5	7.5	87.0	276.1	1.8	5.4	.1	.2	.4	.3
KS	3.3	16.7	418.4	1245.4	0.0	0.1	.6	1.2	2.5	1.6
KY	-6.9	19.8	-173.1	-130.9	-4.1	-12.7	-.1	-.1	-.2	-.1
LA	8.3	20.9	324.0	1000.7	0.0	0.0	.5	.8	1.4	.9
ME	-4.8	16.7	105.3	322.9	8.7	25.2	.1	.2	.4	.2
MD	7.4	20.3	-241.3	-182.6	-2.4	-7.3	-.1	-.1	-.2	-.2
MA	-20.0	57.8	512.5	1572.0	1.0	2.9	.6	.9	1.6	1.1
MI	-40.0	128.7	1186.8	3578.1	5.3	15.0	1.3	2.2	3.7	2.5
MN	-13.9	36.6	132.6	420.5	1.6	4.8	0.1	.3	.4	.3
MS	1.2	2.9	177.1	548.8	0.0	.0	.2	.4	.8	.5
MO	16.2	88.7	347.5	1076.7	5.8	16.8	.6	1.0	1.6	1.1
MT	.2	1.6	-93.6	-70.5	-37.3	-118.7	-.1	-.2	-.3	-.2
NE	.8	4.2	64.6	203.5	3.3	9.8	.2	.4	1.0	0.6
NV	.3	1.6	100.5	306.9	25.8	74.4	.2	.3	.5	.3
NH	-2.6	9.0	94.0	288.3	4.8	13.7	.1	.2	.3	.2
NJ	11.9	30.3	671.7	2060.5	.0	.0	.7	1.2	2.1	1.4
NM	.1	.6	65.4	205.5	.3	1.0	.1	.2	.3	.2
NY	88.5	225.2	1557.4	4777.5	115.0	332.1	1.9	3.2	5.2	3.6
NC	6.7	16.9	-300.8	-227.5	-7.4	-23.0	.1	-.2	-.3	-.2
ND	1.3	6.5	26.6	84.0	5.8	17.1	.3	.4	.5	.4
OH	-48.5	142.7	1391.5	4201.6	0.9	2.6	1.5	2.5	4.2	2.9
OK	4.5	22.9	544.5	1620.5	14.9	42.1	.7	1.1	2.0	1.3
OR	.0	.3	-359.8	-270.5	-179.0	-573.1	-.4	-.6	-1.0	-.7
PA	56.9	142.6	1541.2	4646.9	8.0	22.7	1.8	2.902	4.784	3.288
RI	-3.6	10.3	86.1	264.2	.0	.0	.1	.2	.3	.2
SC	4.2	10.5	-161.0	-121.8	-3.7	-11.3	-.1	-.1	-.2	-.1
SD	.8	3.9	28.7	90.3	14.0	41.3	.1	.1	.2	.1
TN	10.1	25.8	330.6	1024.4	37.0	107.8	.4	.7	1.1	.8
TX	18.4	91.8	2323.3	6981.3	05.9	16.8	2.9	5.0	8.8	5.9
UT	-.2	-.9	-197.8	-148.8	-4.7	-14.9	-.1	-.2	-.3	-.2
VT	-1.7	5.8	47.9	146.8	3.8	11.0	.1	.1	.2	.1
VA	3.8	10.8	-278.9	-211.0	-1.3	-4.2	-.1	-.2	-.3	-.2
WA	-33.8	56.0	-771.9	-578.7	-439.5	-1432.9	-.4	-1.0	-2.1	-1.3
WV	-2.0	3.1	-86.8	-65.6	-0.5	-1.6	.0	-.1	-.1	-.1
WI	-14.4	48.1	149.2	473.2	4.1	12.1	.2	.3	.5	.3
WY	.4	2.0	19.0	59.8	3.2	9.3	.1	.1	.2	.1
US	40.0	1629.	14741.	52244.	-112.	-572.	21.310	35.83	60.46	41.15

NOTE: These results include a downward scaling by a factor of 3.4, so that projected economic growth does not make them look too high in relation to today's economy. Tables 2, 3, and 4 omit this scaling so that the reader can better understand the intermediate calculations that they represent.

FORESTS

Although no one has estimated the nationwide loss of forests resulting from a change in climate, several researchers have estimated the decline in forest biomass. Solomon (1986) applied a forest stand simulation model to 24 sites in eastern Canada and the United States, using climate projections from Mitchell (1983). In an EPA Report to Congress, Urban and Shuggart (1989) and Botkin et al. (1989) examined sites in the southeastern United States and Great Lakes region, using the GISS, GFDL, and Oregon State University Models. Figure 2 illustrates the results of the three studies.[13]

Our approach was to (1) develop generalizing regression equations that express the change in biomass as a function of temperature and precipitation; and (2) use rough estimates of the value of forests to estimate the value of the forest changes. We limited our efforts to the 30 states east of, or bordering, the Mississippi River, excluding Florida.

Change in Biomass

We characterize the Solomon and EPA results separately, given the differences in approach, climate assumptions, and quality of reported results.[14] In specifying our regression equations, we focused primarily on two alternate formulations: (1) modeling biomass as a function of climate and (2) modeling the change in biomass as a function of both climate and the change in climate.

Table 6 shows our equations. The logarithmic equations treat biomass as extremely sensitive to changes in precipitation (elasticities of 12 and 4), because this functional form places excess emphasis on accuracy in cases where the loss is near 100%:[15] Although an elasticity of 4-12 is too sensitive for small changes in precipitation, it understates the sensitivity for large declines in precipitation by a similar percentage.

Temperature was the primary driving factor for all of the modeling studies we used. Our regression equations mostly suggest that the optimal biomass occurs with an annual average temperature of around 8 to 10 degrees, depending on rainfall.

We see no compelling reason to favor one equation over the other; so we treat them as equally valid generalizations of the modeling studies. Because biomass can not be negative, we characterize our uncertainty with a lognormal distribution. (We remind the reader that a best estimate that biomass will decline can still imply that the mean estimate is for an increase in biomass.)[16] Table 7 illustrate summary statistics of the simulations.[17]; Figure 2 compares our best estimates with the estimates of previous studies. We assumed that our simulations had two types of systematic error. (1) for a given state the four projections each have a correlation of 0.5 with one another;[18]and (2) for a given equation, the state-specific projections have a correlation of 0.5.[19]

Value of Forest Changes

Most economic information on the value of forests concerns the value of the timber. Very little has been done to estimate the values of habitat, recreation, natural recharge of water supplies, reduction in air pollution, scenic vistas and screening noise and unsightly infrastructure, providing shade for pedestrians, parked vehicles, and buildings. Moreover, even if we had such studies, they probably would focus on the value at the margin, not the total value. The proper question for someone in Mississippi is not so much "How much would you pay to keep this forest alive" as it is "How much is it worth for the whole region to not look like West Texas?" In the past, these decisions have not confronted us--hence existing analyses would probably understate the values of forests.

Our baseline price assumption considers the observation that forests generally sell for $300 to $1000 per acre less after it is logged. Assuming a 33% tax rate and a 10% rate of return implies that the forests are worth $45 to $150 per acre per year. We assume that the elasticity of demand for forest services is unity.

TABLE 6
Regression Equations Summarizing Forest Modeling Results

Using the results of Botkin *et al.* and Urban & Shuggart

1. $\ln(\mathbf{B}+1) = -9.37 + 0.659\mathbf{T} - 0.0396\mathbf{T}^2 + 9.121\ln(\mathbf{P}) + 3.58\ln(\mathbf{Pjja})$
   (0.223) (0.00735) (2.16) (1.07)
   S.E. = 1.29 $\mathbf{R}^2 = 0.557$ $\mathbf{D}_{15} = 4$ to 6 $\mathbf{T}_{max} = 8.2$

2. $\Delta\%\mathbf{B} = (0.238 + 0.0686\mathbf{P} - 0.0313\mathrm{T})\,\mathbf{T} + 3.2449\,\%\mathbf{P}$
   (0.108) (0.0294) (0.00317) (0.956)
   S.E. = .350 $\mathbf{R}^2 = 0.756$ $\mathbf{D}_{15} = 0.9$ $\mathbf{T}_{max} = 7.6 + 2.2\mathrm{P}$

Using Solomon's result

3. $\ln(\mathbf{B+1}) = -4.08 + 0.547\mathbf{T} - 0.0262\mathbf{T}^2 + 4.39\ln(\mathbf{Pjja})$
   (0.167) (0.00617) (1.79) (1.07)
   S.E. = 0.819 $\mathbf{R}^2 = 0.634$ $\mathbf{D}_{15} = 5.3$ $\mathbf{T}_{max} = 16.2$

4. $\Delta\%\mathbf{B} = (-0.244 + 0.117\mathbf{P} - 0.0146\mathbf{T})\,\mathbf{T} + 0.373\,\%\mathbf{P}$
   (0.111) (0.0371) (0.00259) (0.239)
   S.E.=.166 $\mathbf{R}^2 = 0.49$ $\mathbf{D}_{15} = 29$ $\mathbf{T}_{max} = -16.7 + 8\mathrm{P}$

Note. B = biomass, T = temperature (^{o}C), P = rain (mm/day)
Annual values unless subscripted JJA. Tmax is the temperature at which the model predicts maximum biomass. D15 is the ratio of the sensitivity to a one degree rise in temperature to a 1% increase in rainfall.[21]

Table 7
Costs of Forest Decline from a GISS Doubled CO$_2$

State	Current % Forest Acres million	Change in Biomass Low	Change in Biomass Medium	Change in Biomass High	Cost Divided By Current Value Low	Cost Divided By Current Value Medium	Cost Divided By Current Value High	Cost ($ billions) Low	Cost ($ billions) High
AL	21.73	-80.9	-93.6	-97.9	1.7	2.8	3.90	2.30	8.80
AR	16.99	-68.9	-89.9	-96.7	1.2	2.3	3.40	1.30	5.90
CT	1.82	31.0	-26.0	-58.2	-0.3	0.3	0.90	0.00	0.10
DE	0.40	66.4	-06.3	-47.2	-0.5	0.1	0.60	0.00	0.00
GA	23.91	-1.2	-50.4	-75.1	0.0	0.7	1.40	0.00	3.10
IL	4.26	5.5	-52.5	-78.6	-0.1	0.7	1.50	0.00	.60
IN	4.44	21.3	-32.7	-62.7	-0.2	0.4	1.00	-0.10	.40
IA	1.56	65.7	-36.9	-76.0	-0.5	0.5	1.40	-0.10	.20
KY	12.26	53.0	-14.6	-52.3	-0.4	-2.0	0.70	-0.40	.80
LA	13.88	-41.4	-76.8	-90.8	0.5	1.5	2.40	0.50	3.30
ME	17.71	85.9	09.6	-35.4	-0.6	-0.1	0.40	-0.90	.60
MD	2.63	49.6	-17.2	-54.1	-0.4	0.2	0.80	-.10	.20
MA	3.10	23.7	-30.5	-60.9	-0.2	0.4	0.90	-0.10	0.30
MI	18.22	65.9	-26.8	-67.7	-0.5	0.3	1.10	-0.70	1.80
MN	16.58	224.5	05.3	-65.8	-1.2	-0.1	1.10	-1.60	1.50
MS	16.69	-79.6	-93.3	-97.8	1.6	2.7	3.80	1.70	6.70
MO	12.52	-11.1	-74.8	-92.9	0.1	1.4	2.60	0.10	3.10
NH	5.02	72.0	00.0	-41.8	-0.5	0.0	0.50	-0.20	.20
NJ	1.99	-2.1	-48.4	-72.8	0.0	0.7	1.30	0.00	.20
NY	18.77	40.5	-19.6	-54.0	-0.3	0.2	0.80	-0.50	1.30
NC	18.89	3.7	-46.0	-71.9	0.0	0.6	1.30	-0.10	2.20
OH	7.31	-12.3	-57.2	-79.2	0.1	0.8	1.60	0.10	1.10
PA	17.00	-14.1	-57.4	-78.9	0.2	0.9	1.60	0.20	2.50
RI	0.40	22.1	-31.4	-61.5	-0.2	0.4	1.00	0.00	0.00
SC	12.26	-27.1	-64.8	-83.0	0.3	1.0	1.80	0.30	2.10
TN	13.26	-48.7	-75.7	-88.5	0.7	1.4	2.20	0.60	2.90
VT	4.48	87.4	05.7	-40.4	-0.6	-0.1	0.50	-.20	.20
VA	15.97	22.0	-34.2	-64.4	-0.2	0.4	1.00	-0.30	1.50
WV	11.94	37.6	-24.2	-58.3	-0.3	0.3	0.90	-0.30	0.90
WI	15.32	171.0	17.9	-48.7	-1.0	-0.2	0.80	-1.30	.80
US	(including price uncertainty)							-0.30	57.40

Our cost estimates ignore "substitution opportunities" across states. To the extent that timber is the resource being valued, this assumption clearly tends to overstate the cost. However, most of the other forest values are very site specific and hence substitution is not really an option in the short run. To constrain the calculations from implying absurdly high costs for a given state, we assume that the total cost per acre can not exceed five times the initial value, that is, $225 to 750/acre. On engineering grounds, this assumption seems reasonable since it would probably be possible to irrigate forests at that price.[20]

As Table 5 shows, the projected losses in the southeast are more than enough to offset any possible gains elsewhere. Nevertheless, the reader might logically ask: How could we possibly lose $24 to 60 billion in forests. As a rough check, we note that even the partial studies of forest values are in the same league. For example, annual consumer surplus associated with nonwater recreation in U.S. land is $81 billion (Bergstrom and Cordell, in press). Although not all of it is associated with forests (e.g. historic sites), surely a large fraction is.

Kielbaso and Moll (1987) estimate that the value of trees along streets is $25 billion. The Council of Tree and Landscape Appraisers estimates that street trees represent one-tenth the value of all urban trees (e.g. backyards and parks), which implies that the total value of urban trees is $250 billion; Assuming a real estate cost of capital of 10% implies that the annual services of urban trees is $25 billion. Given that these studies examine but two of the many nontimber uses of forests, it seems reasonable that a large scale loss of forests might be valued in the tens of billions of dollars.

Summary of Results for Doubled CO_2 by 2060

Table 8 summarizes our calculations for a CO_2 doubling by 2060. The GISS scenario implies a (scaled) cost of $37-229 billion; the GFDL scenario, $48-351 billion.

Our estimates for electricity and agriculture are lower than the Smith and Tirpak estimates primarily because they reported actual costs estimated for 2060, while we have scaled these estimates downward to account for economic growth; in addition, we calculate the benefits of CO_2 fertilization assuming a concentration of 600 ppm, whereas Smith and Tirpak recommended 330 and 660 ppm.[21]

Our calculations suggest that the direct economic effects considered by Smith and Tirpak would be overshadowed by the environmental and "quality of life" factors. The costs associated with air pollution, water pollution, lost forests, and health account for 80 percent of the total.

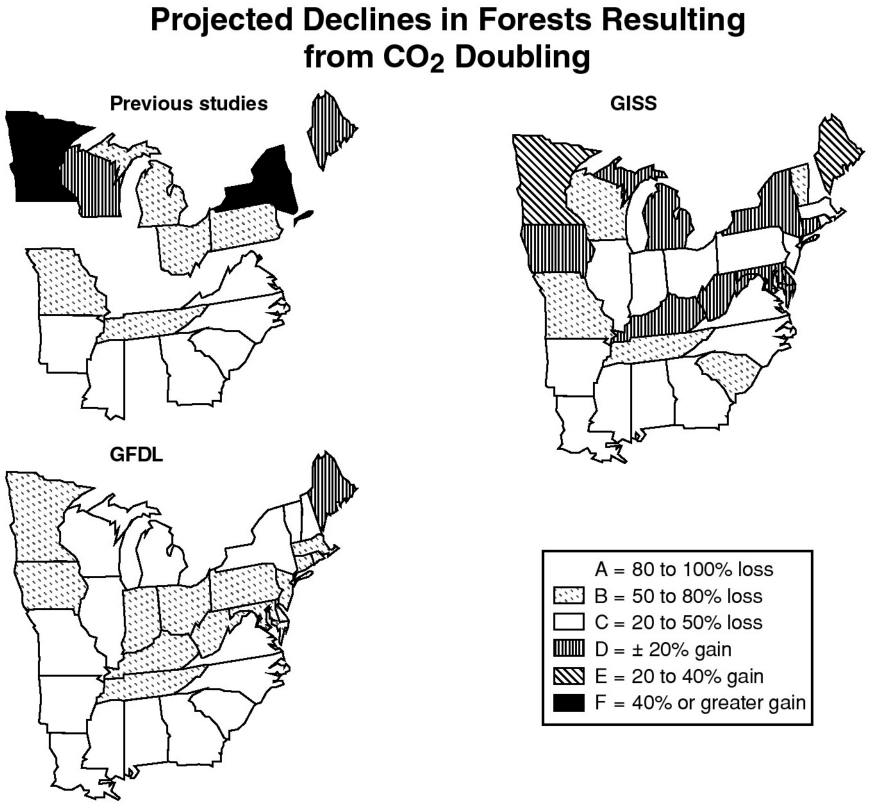


FIGURE 3. Estimates from previous studies reported by Soloman (1986), Botkin et al. (1989), and Urban and Shuggart (1989); states not shown were not examined in those studies. The projections for GISS and GFDL were based on the equations shown in Table 6.

THE BENEFITS OF SLOWING THE CHANGE IN CLIMATE

The preceding estimates illustrate our assumed sensitivity of various sectors to a change in climate. But policymakers need to know the benefits of particular policies, which requires examining (1) how the costs will rise through time with no policy; and (2) the benefit (reduction in costs) of implementing a particular policy.

Costs of Climate Change Through Time

Like the IPCC, we relied on EPA's Atmospheric Stabilization Framework for estimates of concentrations and temperatures through 2100,[22] which assumes a three-degree temperature sensitivity, and hence, less warming than the Smith and Tirpak study. The model projects a global warming of 4.6 degrees by 2100, with a change in concentrations sufficient to eventually cause a 6.8 degree warming. We assume that concentrations remain constant after 2100, and that global temperatures approach the equilibrium with an e-folding time of 40 years. Figure 3 illustrates the resulting estimates of temperature and sea level; note that substantial warming has already occurred.

We estimated transient regional scenarios of temperature and precipitation by interpolating and extrapolating the GISS and GFDL estimates according to the ratio of the transient temperature to the equilibrium temperature of the model. Thus, we remove any (perceived) upward bias associated with these two models; we only use GISS and GFDL to allocate climate change across regions, not to estimate global warming.

Table 8
Scaled Cost in the Year 2060

	GISS				GFDL			
	Low	Medium	High	Mean	Low	Medium	High	Mean
Agriculture	-7.60	-2.80	1.40	-3.10	-3.90	5.10	14.00	5.10
Electricity	2.40	5.60	13.30	8.10	2.40	5.60	13.30	8.10
Sea Level	1.70	5.70	19.10	11.80	1.70	5.70	19.10	11.80
Ozone	9.50	21.80	50.30	30.90	14.10	32.60	75.40	46.30
Mobile A/C	1.10	1.80	3.10	2.10	2.30	3.10	4.30	3.30
Health	2.50	9.90	31.80	20.00	2.50	8.90	31.80	20.00
Forests	-0.30	28.50	57.40	30.40	4.20	58.70	113.20	58.70
Water Resources	21.30	35.90	60.50	41.10	31.10	52.00	87.20	59.50
Surface Water								
Demand	0.04	0.25	1.80	1.67	1.06	2.33	5.17	2.33
Supply	0.64	1.68	4.50	1.68	0.89	2.28	5.81	3.53
Ground Water								
Demand	0.23	0.53	1.30	0.77	0.27	0.73	1.97	1.19
Supply	0.63	1.68	4.50	2.71	0.89	2.28	5.81	3.53
Water Pollution								
Public	2.19	5.81	15.40	9.30	3.71	8.42	19.10	11.80
Industrial	12.50	21.50	36.70	24.80	18.06	29.40	47.90	33.10
Hydropower	-0.11	-0.35	-0.57	-0.35	1.30	2.21	3.77	2.55
Residential	0.04	0.25	1.60	1.38	0.10	0.50	2.50	2.21
Total	37	92	229	139	48	130	351	212

Figure 4 shows GISS transient estimates of the (scaled) costs of climate change. As expected, sea level rise peaks after the year 2100 because by this time most wetlands have been inundated; a second peak occurs a century later when the substantial concentration of development between 1 and 2 meters is inundated.[23] Under the GFDL scenario, agricultural costs diminish at first, as agriculture becomes a smaller portion of the total economy; they later increase as the adverse impacts begin to grow more rapidly than the general economy. By contrast, the GISS scenario shows substantial near-term benefits from CO_2 fertilization. The other impacts rise with the change in climate.

Impacts of an Example Policy

For illustrative purposes, the easiest policy to consider is a small temporary reduction in emissions. We assume that during the decade 1995-2005, emissions of CO_2 are reduced by 10 billion metric tons of carbon, but that emissions are the same after 2005 as in the baseline.[24] As Figure 5 shows, the impact of such a reduction reaches a peak a of 0.044 a few decades later. However, because CO_2 remains in the atmosphere for centuries, the impact declines very slowly. Therefore, any reduction in emissions today would yield benefits well into the next millennium. As Figure 5 shows, the benefits would be about $1-2 billion during much of the next century.

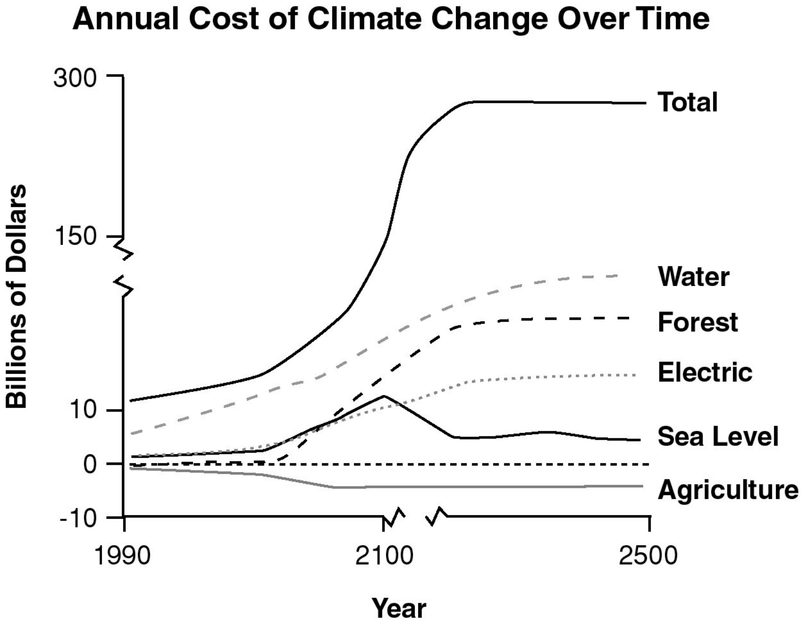


FIGURE 4.

Discounting

How much should we be willing to pay today to save to save a billion or so dollars per year for the next several centuries? Ultimately, the answer depends on whether or not we care about future generations. Economists generally assume that public policies should make no distinction between generations; i.e. that we care as much about a future generation as about our own. However, a dollar invested today will be worth $10 at some future date. Therefore, when economists say that we should not spend $1 to save a future generation $5, they are not saying that future generations are less important than our own; they are saying that the future generation will be better off if we invest the $1 in an investment that will yield $10.

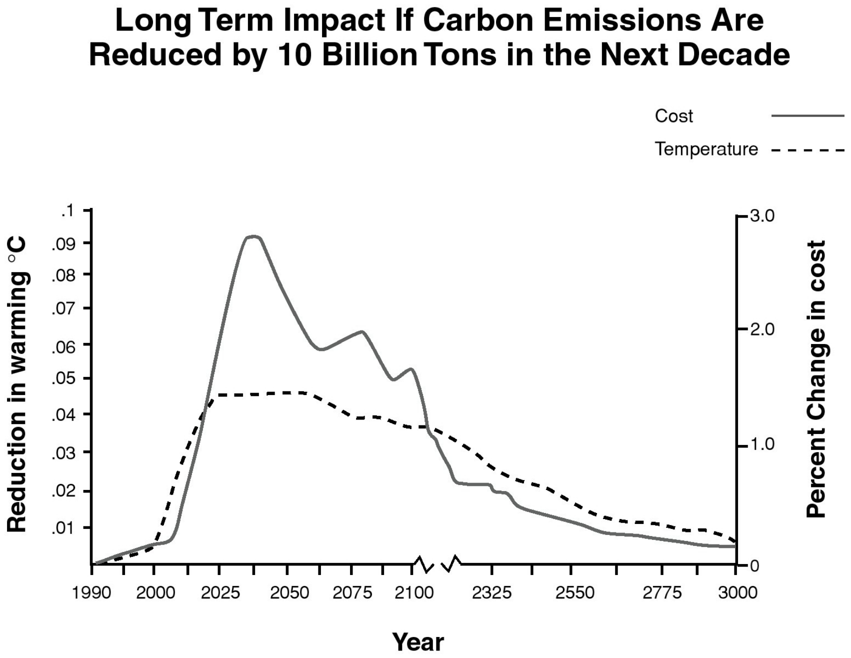


FIGURE 5.

The problems with this approach are that (1) we do not know the extent to which the funds for reducing emissions will come from investment or current consumption; and (2) to the extent that it comes out of investment, we do not know what the foregone investment would have otherwise yielded. There are numerous solutions to each problem; but none are fully satisfactory. The theory of portfolio management offers the most thorough and tested approach for deciding on the required return of an investment.

Unfortunately, the approach has never been rigorously applied to determine the appropriate return for global warming and other long-term environmental problems. For a stock to be held for one year, the capital asset pricing model shows that the required return is a linear function of the extent to which the investment increase the overall riskiness of the investor's portfolio. If there is no risk (e.g. U.S. Treasury Bill), we assume that the investment has a pretax inflation adjusted return of 4 percent. Financial analysts generally agree that a fully diversified portfolio (annual risk of about 15 percent) requires an extra 4-1/2 percent return to account for the risk, i.e. 8-1/2 percent[25]. A stock that rises or falls with, but twice as much as the market would require twice the risk premium (9 percent), for a total return of 13 percent. Selling short on the same investment implies that when the market falls 1 percent, the investment rises 2 percent; thus, there is a risk premium of -9 percent, implying a required return of -5 percent per year.

If a stock is to be held for 30 years, the investor does not bear 30 times the risk of holding the stock for one year. For a random walk, the standard deviation rises with the square root of the number of years. Thus, the required return for a typical investment being held for 100 years would be 1.04100*1.045 10=78.38 rather than 4117. Even this calculation overstates the risk over the period: The standard deviation would be 160% of the initial investment; but unless one is buying options the risk in reality is never greater than the investment itself.

The returns of environmental investments are probably not correlated with the stock market; the scientific uncertainties have nothing to do with Wall Street. But extending the analysis to consider other principal components of societal wealth suggests that there is probably a strong negative correlation between the return from efforts to stop global warming and the state of the environment. The principals of portfolio theory require us to consider how our uncertainty regarding an investment is related to our overall portfolio, which includes the environment, income, and economic assets not traded in the market. Efforts to slow global warming are least likely to be important if the environment is in good shape, whether that condition results from a failure of global warming to materialize or environmental policies that are strong enough to allow nature to survive, or a technological leap forward that give us the wealth or reduce the costs to enable us to solve environmental problems that today seem prohibitively expensive. Moreover, a strong economy is probably less vulnerable to climate change than a weak economy. Thus, the use of financial theory would lead us to either (1) use a discount rate less than the risk-free rate; or (2) estimate the value of reducing the uncertainty, and discount the result using the risk-free rate. To ensure that we avoid anomalous negative discount rates, we opted for the latter approach. Our calculations already estimate the standard deviation of our uncertainty for a given model. We assume that model error and our ignorance about the future triples that uncertainty, and we apply that risk/return tradeoff implied by the capital asset pricing model. For example, if our projected cots of climate change has a median of $100 with a standard deviation of 15%, we would value that impact at $104.50; if the uncertainty is 150% of the median, we would value the impact as $145.

Over the last century, the average rate of return on Treasury Bills has been less than 2 percent adjusted for inflation; the last few decades, however, has seen a rate closer to 5 percent. Moreover, taxes distort the picture: The after-tax rate may reflect how people weigh the present against the future. However, the total cost to society of forgoing an investment must include the taxes that are lost as well. Because most investments are taxed at a rate lower than the risk-free rate, however, the appropriate return probably falls somewhere between these two rates. Thus, our calculations use the 2, 3, and 4 percent discount rates.

Table 9 illustrates our calculations, with the results expressed in terms of cents of damages per gallon of gasoline. Our results are consistent with the hypothesis of Cline (1991) that the impacts of global warming are understated unless one looks at the very long run. With a 4 percent discount rate, most of the costs occur before the year 2100. By contrast, with a 2 percent rate, the costs are 29-43 cents per gallon through 2100, but the total cost is 97-135 cents per gallon. While we assume that concentrations are stable after 2100, Cline (1991) assumed that they will continue to increase for another century. Had we adopted his assumption, the additional costs of burning a gallon of gasoline would appear to be even greater.

Table 9
Marginal Costs of Climate Change from Burning One Gallon of Gasoline
(present value in cents per gallon)

Model	**Discount Rate**		
	2%	3%	4%
GISS			
Before 2100	28.7	16.5	10.3
Long Run	97.0	24.7	12.0
GFDL			
Before 2100	42.6	25.2	14.0
Long Run	135.6	36.5	18.6

NOTE: These calculations assume that the ratio of worldwide to U.S. damages will be the same as the ratio of emissions (i.e., five). They also assume that the baseline concentration of greenhouse gases does not increase after the year 2100, implying an equilibrium warming of 6.8 degrees.

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NOTES

1. See parallel effort by Cline (1991).
2. We have adjusted their figures to 1990 dollars.
3. Nordhaus (1990) estimates that the savings would be about $1.6 billion per year.
4. The IPCC model probably overstates the short-term contribution of mountain glaciers, but is otherwise superior to other efforts because the rate of melting depends upon the amount of snowcover remaining.
5. Even on a 90 degree day, some people will drive at night when it is cooler and hence not need their air conditioner-, by contrast, even on a 60 degree day, a large portion of the driving will occur during the day.
6. We simply calculate the mean and standard deviation of the samples and divide the latter by the square root of the sample size.
7. Note, that Smith and Tirpak's summary of these results indicates that ozone concentrations will rise about 10 percent.
8. For more details on our water resource and forest calculations, detailed appendices are available from the author.
9. Elasticity refers to the percent change in quantify supplied or demanded for a 1 percent change in price.
10. The referenced publications describe the analysis undertaken and some of the general results. However, only Rosensweig published the site-specific results.
11. We matched the Great Lakes equations with USGS water regions 1, 4, 5, 7, and 9, as well as the state of Washington; the southeast with regions 2, 3,6, and 8; and the Great Plains results with the rest of the nation.
12. This distinction was necessary because the relatively fixed supply of dams in the midst of plentiful surface water in the east implies that supply is inelastic when demand shifts but effectively elastic runoff changes.
13. Note that the figures for Solomon are estimates based on reading the graphs published in the article. Solomon has changed jobs and thrown away the raw data on which the figures were based. We also had to estimate the climate change that Dr. Solomon had 32 used in the model runs; the results were based on a 1983 run of the United Kingdom Meteorological Office's model. Dr. Mitchell of the UKMO told us that they had thrown away their raw data as well. Finally, the reader may note that Boikin failed to report a number of his results. We attempted to secure from Boikin his unreported results, but he declined to cooperate.

14. We relied on historic climate data provided by Roy Jenne and Dennis Joseph of the National Center for Atmospheric Research. We had to omit a few of the Solomon sites from our analysis because NCAR had no available weather data at those sites.
15. The act of minimizing a sum of squares treats, the difference between a 10 and 50 per-cent loss in biomass as less than the difference between a 98 and a 99 percent loss, even though for most purposes we would be more interested in the former distinction. On the other hand, the arithmetic form treat the first 50% loss as the same as going from 50% to zero. When considering the value of losing a forest, the last increment is particularly important. The problem is that the model accuracy is probably closer to arithmetic; hence focussing on the loss of that final 5% is pointless since the models we are trying to mimic are not that accurate anyway. One of our reasons for using arithmetic percentage decline and logarithms is that neither form is ideal, but their weaknesses are complementary.
16. Statistical theory show that the variance of a mean which declines with the sample size if observations are independent. We assumed that the projections for a given state had 0.5 correlations with one another.
17. These statistics are for exposition and model evaluation only. As mentioned in the previous paragraph, our cost estimates were based solely on the mean and variances of the logarithm of the change in biomass for each state.
18. On statistical grounds, the R-square values approaching 0.75 make a good case for a correlation of 0.5. According to regression theory, oversimplifications and omitted explanatory variables only cause systematic error if those variables are correlated with the variables included in the model. It seems that some of those variables are fairly random, while others are systematic.
19. Given that each equation accounts for 1/4of the projection, it is straightforward to show that assumption implies [hat a correlation of 0.125 between the projections for differential states. Implied variance is thus: variance = $0.125* (\Sigma\sigma)^1 + .875* \quad \Sigma\sigma^2$
20. We may be assuming an artificially low price of water that climate change will invalidate. Future should probably calculate the amount of water necessary to 33offset the impact of climate change and use the water price assumed to result from climate change.
21. IPCC projects the CO_2, equilibrium climate to occur somewhat after 2060; by that time, it projects a CO_2, concentration of 600 ppm.
22. We are grateful to Bill Pepper of ICF Incorporated, the model's principal investigator.
23. An additional 60 cm of baseline sea level rise also occurs by this time.
24. Such a reduction is equivalent to 12 percent of projected emissions for that period, or about 80 billion barrels of oil.
25. E.G. Sharp, W. 1990. Investments, Chapter 23. New York: Prentice-Hall.